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Reducing ion beam noise of vacuum arc ion sources

André Anders[1] and Ralph Hollinger[2]
[1]Lawrence Berkeley National Laboratory, University of California,
1 Cyclotron Road, Mailstop 53, Berkeley, California 94720, USA
[2]Gesellschaft für Schwerionenforschung, Planckstrasse 1, 64291 Darmstadt, Germany

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Abstract

Vacuum arc ion sources are known for delivering high currents of metal ion beams. By Langmuir probe and Faraday cup measurements it is shown that fluctuations of the ion beam current are due to the fluctuations of plasma density which in turn are due to the explosive nature of plasma production at cathode spots. Humphries and co-workers and later Oks and co-workers have shown that beam fluctuations can be reduced by inserting biased meshes in the plasma. Here, the idea of ion extraction at kV-level with post-acceleration is investigated. The high voltage allows us to use coarse, ridged meshes or grids. The combination of an extractor operating in the overdense plasma regime with post-acceleration lead to very reproducible, practically "noiseless" ion beams however at the expense of low ion current density. The noise reduction is due to ion optics effects. Although the current setup is not suitable for a heavy ion fusion injector due to the low beam current and the risk of extractor voltage breakdown, further development of the concept may lead to reproducible beam pulses of sufficiently high current and brightness.

I. INTRODUCTION

Vacuum arc ion sources, also known as Mevva ion sources, can deliver high-current ion beams of virtually all solid conducting materials[1]. Ions are extracted from fast streaming, high density metal plasma that originates at cathode spots. Ion extraction is accomplished using three multi-aperture grids of the common acceleration-deceleration configuration.

The quality of an ion beam in terms of ion current density and emittance critically depends, among other parameters, on the position and shape of the plasma boundary[2]. As illustrated in Figure 1 (left), the plasma density needs to be well matched to the given extractor geometry and extraction voltage to obtain a high-current, high brightness beam (perveance matching). Fluctuations of the plasma density do not only represent fluctuations in terms of ions available for extraction but they translate into fluctuations of the *shape* of the plasma boundary followed by fluctuations of ion beam current (Fig.1). Therefore, in order to obtain well-reproducible, predictable and low-noise beam parameters, the plasma must be reproducible and quiescent. Unfortunately, vacuum arc plasmas are rapidly fluctuating due to explosive plasma formation at cathode spots[3,4].

More than a decade ago, vacuum arc ion sources had already been considered for heavy ion fusion (HIF). Humphries and coworkers[5,6] introduced fine grids to control plasma flow, suppress beam noise and improve the poor pulse-to-pulse reproducibility. Encouraging results have been obtained[7] but the survival time of the very fine grids and meshes was unsatisfactory.

More recently, vacuum arc ion sources are again considered for HIF[8,9]. Oks and coworkers combined fine meshes with stabilizing holding grids[10,11], demonstrating significant reduction of beam noise, see also the companion paper[12].

The use of very fine, biased meshes within the plasma has several drawbacks including the risk of arcing leading to the destruction of the mesh, and a change of the geometrical transmission due to plasma deposition on the mesh. A very rugged "mesh" is a grid system of relatively large size; the grid's holes being of order 1 mm, or larger, rather than tens of micrometers. In order to prevent the dense vacuum arc plasma from flowing though the grid holes, one needs to apply relatively high grid voltage such as to make the sheath thickness much larger than the radius of the grid holes. The self-adjusting sheath thickness at a biased metal in a vacuum arc plasma can be estimated by the Child law in the form[13]

$$s = \frac{2}{3}\left(\frac{2\,\varepsilon_0^2\,\phi^3}{m_i\,\overline{Q}e\,n_{i0}^2\,v_{i0}^2}\right)^{1/4} \tag{1}$$

where ϕ is the grid potential with respect to the plasma potential, $\overline{Q}$ is the mean ion charge state number, n_{i0} and v_{i0} are the ion density and velocity of the directed streaming velocity at the sheath edge.

In this work, we report about an attempt to obtain low-noise ion beams using a relatively coarse, mechanically ridged grid system (as opposed to a fine mesh) operating at relatively high voltage (kV as opposed to tens of volts). One may consider this grid system as an ion extractor that is followed by a second extraction system (post-accelerator).

II. TECHNICAL APPROACH AND EXPERIMENTS

2.1. Plasma density and beam current correlation

For a first round of experiments, a "usual" vacuum arc (Mevva) ion source setup[1,12] without additional meshes or grids was used. The ion density was measured with a small Langmuir probe placed in the expanding vacuum arc plasma. The probe was operating in the ion saturation regime and the signal was transferred from high potential to ground potential via glass fiber cable.

Fluctuations of the ion flux translate directly to fluctuations of the ion beam current density if the plasma density is perveance-matched or lower. The left part of Figure 2 shows the ion density of titanium plasma prior to extraction, and the titanium ion beam current after extraction. The ion beam current was measured using a Faraday cup. One can easily identify correlation of ion density and beam current fluctuations.

If the supply of ions from the flowing vacuum arc plasma is greater than the ion current determined by the Child law, i.e.,

$$j_i = \overline{Q}\, e\, n_{i0}\, v_{i0} > j_{i,Child} = \frac{4}{9}\varepsilon_0 \left(\frac{2\overline{Q}\, e}{m_i}\right)^{1/2} \frac{\Phi^{3/2}}{d^2} \tag{2}$$

the plasma boundary starts bulging into the gap between grids, thereby effectively reducing grid spacing and also causing ion beam quality to deteriorate; Φ is the potential difference of the grids having a distance *d*. A further increase in plasma density enhances the effect and may lead to voltage breakdown between grids.

Interestingly, even a traditional accel-decel system is self-stabilizing from a beam current point of view[14]. The greater the plasma density, the stronger the bulging, the more beam ions are lost due to poor ion optics (right sides of Figs.1 and 2). If the plasma density is increased, for instance by increasing the arc current, or by efficiently guiding the plasma to the extraction system with the help of an axial magnetic field, the correlation between plasma density fluctuation and ion beam fluctuation is lost (figure 2 right). The plasma boundary will bulge into the space towards the next grid (Fig. 1 right) and thus cause more ions to diverge from the parallel trajectory. “Bulging” of the plasma boundary and supply of ions in the plasma flow are correlated. The intentional mismatch leads to a relatively constant ion beam current, which is, however, less than the maximum current that can be obtained from the grid for a given voltage at matched conditions[14].

2.2. System consisting of ion extractor and post-accelerator

Instead of using fine meshes, we investigate here an experimental setup that utilizes an accel-decel extraction system operating in the overdense regime, followed by a 70 mm long drift region where the beam thought to be fully space-charge-compensated due to secondary electrons, and finally a post-acceleration grid system giving ions high energy (Fig 3).

We used a number of extraction grids and various distances and voltages; we restrict this report to the most relevant setup and results. Each grid of the extraction system had a pattern of 61 holes, drilled in a sheet of 1.5 mm thick stainless steel; the hole diameter was 2.0 mm in the grid seen first by the streaming plasma (sometimes called the plasma grid) and 2.4 mm in the other grids. The grids where insulated by PEEK spacers (a high-temperature plastic). The distance between the plasma grid and the suppressor grid, and the suppressor grid and outlet grid was 3 mm and 1 mm, respectively. The distance between cathode and the plasma grid was 50 mm, and the distance between the outlet grid and the first grid of the post-accelerator was 70 mm.

The post-acceleration voltage was always kept much higher than the extraction voltages (30 kV versus max 8.2 kV, respectively). By varying the post-acceleration voltage it was checked that the ion beam current, as measured by a Faraday cup 20 cm downstream of the post-accelerator, did indeed not depend on the post-acceleration voltage but solely on the voltage setting of the first extraction system. Figure 4 shows the current of a single-pulse ion beam of 600 µs duration with two zoom settings of the storage oscilloscope. The overall pulse can be seen with 100 μs /div while the zoom resolution is 10 μs/div. The beginning of pulse is shown in the left part of figure 4. During the rise time of the arc discharge, the plasma density increases and the extracted ion beam current has a maximum when the density reaches perveance matching for the given extractor geometry and bias setting. For the main part of the pulse, the extractor is operated in the overdense regime thus the ion current is less than maximum. The post-accelerated ion beam current is virtually "noiseless" as shown in the right part of figure 4; the noise level is within the limits of measuring accuracy. At the end of the arc discharge pulse, the plasma density drops and briefly goes through perveance-matching, causing a second peak in the ion beam.

III. DISCUSSION AND CONCLUSIONS

The degree of noise reduction obtained with two extraction systems in series is greater than what has been obtained with the operation of one extractor in the overdense regime[14], or using biased fine meshes in the plasma flow[7,12]. The effect is due to the feedback of increased beam losses when more ions are supplied by the plasma than can be transported at perveance matching, i.e. ion an optics effect in and after the first extractor. The second extraction system in series, or post-accelerator, is thought to produce a high-quality beam, though at a much lower current density than in the first extractor system. The beam quality still remains to be determined. While the current density in the first system is about 70 mA/cm^2, the measured maximal ion current was 6 mA in the Faraday cup after post-acceleration in the present setup. By using much higher voltages (10s of kV) and grid materials that tend to suppress voltage breakdowns, one may be able to increase the usable ion current after the post-accelerator to a level relevant to accelerator injectors.

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Figure Captions

Figure 1. Schematic illustration of ion extraction from a plasma; left: perveance-matched plasma density; right: overdense plasma.

Figure 2 Ion density in the plasma prior to extraction (Langmuir probe, placed in the expanding vacuum arc plasma and operating in the ion saturation regime at –100 V, 1 mA/div) and the ion beam current density (Faraday cup via 50 Ω to ground, 2 mA/div). Ti plasma; 10 kV extraction voltage. (a) 150 A arc discharge current; (b) 250 A.

Figure 3 Schematic of the vacuum arc plasma generator (arc cathode and anode), space charge filter, and ion extraction system; the lower part of the drawing shows the potential distribution.

Figure 4 Ion beam current from a 250 A titanium arc; ions went through the space charge filter and extraction system with the following potential steps (see figure 3); -8.2 kV, +1.6 kV, -30 kV, +3 kV.

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